Un-modeled search for black hole binary systems in the NINJA project

Laura Cadonati[1], Shourov Chatterji[2,3], Sebastian Fischetti[1], Gianluca Guidi[2,4], Satyanarayan R. P. Mohapatra[1], Riccardo Sturani[2,4], Andrea Viceré[2,4]

[1] Department of Physics, University of Massachusetts, Amherst, MA 01003

[2] INFN-Sezione Firenze, I-50019 Sesto Fiorentino, Italy

[3] LIGO – California Institute of Technology, Pasadena, CA 91125, USA

[4] Istituto di Fisica, Università di Urbino, I-61029 Urbino, Italy

E-mail: `cadonati@physics.umass.edu`

Abstract. The gravitational wave signature from binary black hole coalescences is an important target for LIGO and VIRGO. The Numerical INJection Analysis (NINJA) project brought together the numerical relativity and gravitational wave data analysis communities, with the goal to optimize the detectability of these events. In its first instantiation, the NINJA project produced a simulated data set with numerical waveforms from binary black hole coalescences of various morphologies (spin, mass ratio, initial conditions), superimposed to Gaussian colored noise at the design sensitivity for initial LIGO and VIRGO. We analyzed this simulated data set with the Q-pipeline burst algorithm. This code, designed for the all-sky detection of gravitational wave bursts with minimal assumptions on the shape of the waveform, filters the data with a bank of sine-Gaussians, or sinusoids with Gaussian envelope. The algorithm's performance was compared to matched filtering with ring-down templates. The results are qualitatively consistent; however due to the low simulation statistics in the first NINJA project, it is premature to draw quantitative conclusions at this stage.

PACS numbers: 04.80.Nn, 04.30.Db, 04.30.-w, 04.25.D-, 04.25.dg,

1. The NINJA Project

The Numerical INJection Analysis (NINJA) project [1, 2] is a collaboration of numerical relativists and gravitational-wave data analysts, with the goal to improve detectability of binary black hole (BBH) coalescences with numerical relativity waveforms. The first NINJA project represented an important step towards the use of numerical waveforms to enhance the performance of data analysis. Nine numerical relativity groups shared waveforms for BBH coalescences, with no restrictions on spin, eccentricity, or mass ratio, and ten data analysis groups analyzed them with various methods based on both modeled (i.e. matched-filtering) and un-modeled searches. Numerical relativity can now provide complete coalescence waveforms, from *inspiral* to *ring-down* of the final remnant, through the *merging* of the black hole constituents of the binary system. A recent review of the status of binary black hole simulations is available in [3]. In the absence of signals from real sources, these waveforms offer a unique opportunity to test the data analysis search pipelines for efficiency in detection and faithfulness in source parameter estimations. The collaboration has been open to all scientists interested in numerical simulations.

To model the detector, Gaussian noise time series have been generated, colored with the design sensitivity of each of the LIGO [4, 5], and VIRGO [6] detectors. Non-Gaussian noise transients and narrow band features like violin and mirror modes, typical of real detector noise, are not included. A population of simulated gravitational signals has also been produced, from numerical relativity data. Such population covers a broad range of black hole masses, distances and orientations. For the numerical waveforms that were used see [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22], for descriptions of the numerical codes see [23, 24, 25, 12, 26, 27, 18, 28, 29, 30, 31, 22]. For details on the parameters, we refer to [1, 2].

Matched filtering of the noise data endowed with simulated signals have been performed with analytical waveform models of the inspiral stage, from Post-Newtonian expansion [32], and with hybrid models of the full coalescence, created by matching Post-Newtonian perturbation templates with numerical relativity waveforms [33]. In addition, matched filtering to ring-down waveforms targeted high mass systems: the larger the mass of the black holes, the smaller is the frequency of the coalescence. Since the ring-down is at higher frequencies than the chirp signal from the inspiral, ring-down templates are particularly useful to detect the high mass BBH systems. Un-modeled searches, that do not rely on templates, have been performed with the Q-pipeline and Hilbert Huang Transform [34]. Parameter estimation techniques were also tested on this data set [35, 36]. For details and comparisons on the analysis pipelines and their performance in the NINJA project, see [1].

This paper compares the performance in the first NINJA project of two algorithms, developed by the LIGO Scientific Collaboration (LSC) for searches of bursts and ring-downs: *Q-pipeline* [37, 38, 39] and *lalapps_ring* [40, 41]. The algorithms are applied to the output of a single simulated detector, Hanford LIGO, whose data span a duration

of little over 30 hours. Sec. 2 describes the analysis, sec. 3 presents the results, and conclusions are drawn in sec. 4.

2. The Analysis

In this section we provide some detail on the two algorithms we used in this study, and how they are implemented.

2.1. Burst techniques: Q-pipeline

The *Q-pipeline* [37, 38] is one of the algorithms used by the LIGO Scientific Collaboration (LSC) in the search for gravitational wave bursts [42]. It is a multi-resolution time-frequency search for statistically significant excess signal energy, equivalent to a templated matched filter search for sinusoidal Gaussians in whitened data. The template bank is constructed to cover a finite region in central time, central frequency, and quality factor Q_q, the number of oscillations under the gaussian envelope, which, up to a constant, is the ratio of central frequency to bandwidth of the signal. The mismatch between any sinusoidal Gaussian in this signal space and the nearest basis function does not exceed a maximum mismatch of 20% in energy. For this study, as in [42], the data is analyzed in 64 sec blocks, in the frequency range 48-2048 Hz, with Q_q between 3.3 and 100.

2.2. Matched filtering to ring-downs

The *lalapps_ring* [40, 41] code has been developed by the LSC for ring-down matched filtering searches. For this study, we used the same version as in the LIGO S4 ring-down analysis [43, 44]. The template bank is made of sinusoids with given frequency damped with an exponential, covering the parameter range 50-2000 Hz in frequency and 2-20 in Q_{rd}, being Q_{rd} π times the damping time in unit of the sinusoid period. The analysis is performed in overlapping blocks of 2176 seconds; the low-frequency cutoff is 45 Hz for the LIGO noise curves and 35 Hz for the VIRGO noise curve.

2.3. Analysis strategy

The ultimate goal of this study is a multi-detector analysis, inclusive of a coherent followup that checks for sky location, and an event-by-event comparison of triggers from inspiral, burst and ring-down analyses, to explore the three phases of the coalescence, using Q-pipeline, lalapps_ring and inspiral matched filtering triggers produced by one of the other NINJA analysis teams [1].

However, for the first NINJA release, we forewent the coherent followup step and instead focused on single-detector results: we established a nominal threshold signal-to-noise ratio (SNR) of 5.5 and estimated parameters from the two pipelines to nominal

parameters: the time of the waveform maximum $T_{\rm peak}$, the innermost stable circular orbit (ISCO) and ring-down frequencies $f_{\rm ISCO}$ and $f_{\rm ring}$ [45, 46, 47, 48]:

$$\begin{aligned} f_{\rm ISCO} &= \frac{c^3}{6\sqrt{6}\pi G(m_1+m_2)}\,, \\ f_{\rm ring} &= \frac{c^3}{2\pi GM}\left[1-0.63(1-a)^{0.3}\right] \end{aligned} \qquad (1)$$

where G is the Newton constant, c the speed of light, $m_{1,2}$ the individual constituent masses and a, M are the final black hole dimension-less spin and mass calculated as in [49] and [50], respectively. The injected SNR is computed from the signal before injection and mean detector noise spectrum with starting frequency as specified in sec. 2.2. The threshold choice is consistent with S4 ring-down and S5 burst analyses [42, 44]. A more accurate threshold selection would require a study of accidentals and a fine tuning that goes beyond the scope of this initial study.

3. Results

Unless otherwise stated, all the results discussed in the following sections are restricted to the 4 km Hanford detector (H1): given the limited statistics (94 signals injected with SNR$\geq$ 5.5), a full discussion of all interferometers would not reliably provide further insight in addition to the information presented below.

3.1. Detection Performance

The NINJA project paper [1] provides a comparative analysis of the different methods employed (inspiral, hybrid and ring-down templates for matched filtering, Q-pipeline and Hilbert Huang transform for burst searches). Here we focus on the analysis performed by un-modeled search via the Q-pipeline and by the matched-filtered one using ring-down templates, both at the single interferometer level, with the same nominal threshold of $\text{SNR}_{\rm measured} \geq 5.5$. The statistics of this sample is too small to make inferences on which pipeline performs better in which parameter region; a more systematic study is needed to assess the power of the methods. Also, this analysis does not take into account the effect of background noise transients and accidental coincidences, which are very different in real data than in Gaussian noise, so this comparison is not complete. Nevertheless we have an indication that all pipelines have comparable chances to find these signals.

Figure 1 shows plots of all the injections used in the NINJA project as a function of injected SNR and total mass, identifying which were missed and found by Q-pipeline and lalapps_ring, respectively; black circles are injections found with SNR$\geq$ 5.5, the red stars are missed. Out of 94 signals with injected SNR$\geq$ 5.5, 88 (88) were found by Q-pipeline (lalapps_ring) and 89 (87) were found by Q-pipeline or (and) lalapps_ring with measured SNR$\geq$ 5.5. A comparison of the difference between injected and measured SNRs can be seen in Figure 2, where we plot the SNR detected respectively by the Q-pipeline and the ring-down search as a function of the injected SNR. Notice that in both

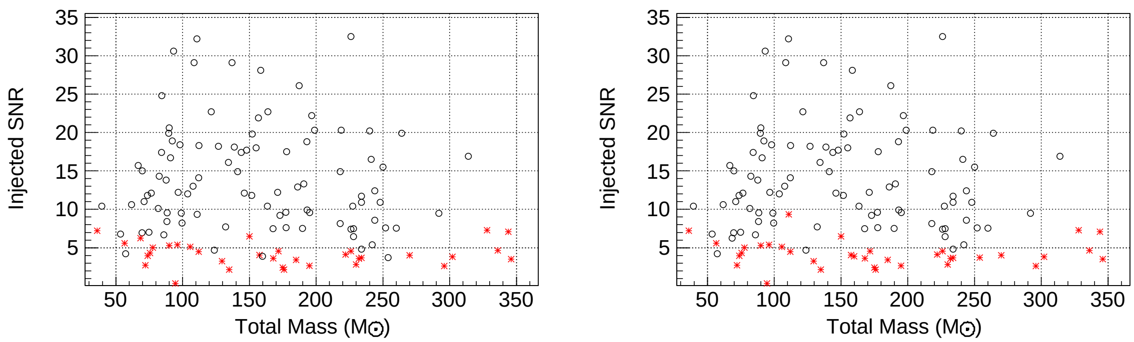

Figure 1. Injections that were missed (stars) and found (circles) by Q-pipeline (left) and by the ring-down matched filtering (right) in H1 as a function of SNR and total mass. For both algorithm, the condition for an injection to be *found* is that the measured signal-to-noise ratio is $\mathrm{SNR}_{\mathrm{measured}} \geq 5.5$.

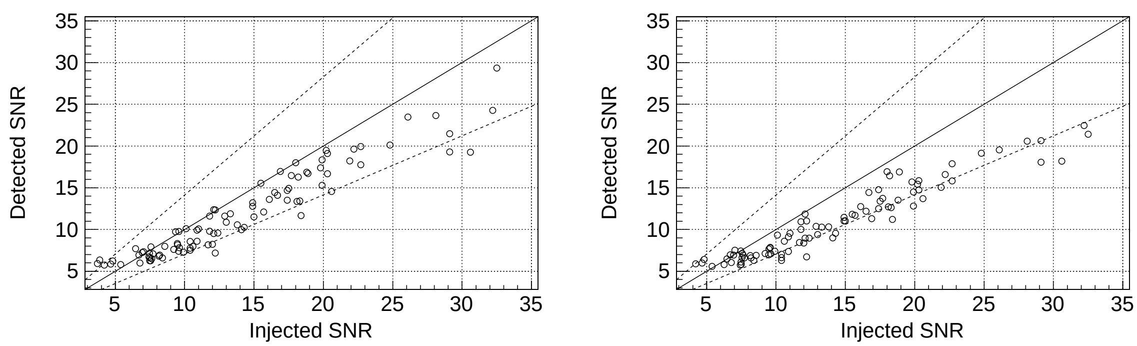

Figure 2. SNR detected by by Q-pipeline (left) and by the ring-down matched filtering (right) as a function of injected SNR for found injections. Dashed lines indicate a deviation from the diagonal by a factor of $\sqrt{2}$.

cases the detected SNR is smaller than the injected SNR (for SNRs above threshold), which is consistent with Q-pipeline detecting only a portion of the signal. There are few event at the detection threshold where the detected SNR is larger than injected SNR, due to noise fluctuation near threshold. For stronger signals, the discrepancy between measured and injected SNR is roughly within a factor of $\sqrt{2}$, indicated by the dashed lines in Figure 2.

To compare the detection efficiency of Q-pipeline with lalapps_ring, in Figure 3 we also plot the SNR recovered by lalapps_ring against the one recovered by Q-pipeline. Note that Q-pipeline finds injections with a slightly larger SNR; however, the detection performance of the two algorithms is relatively consistent. Here, the same detection threshold SNR ≥ 5.5 was used for both searches; in a real search, different thresholds may be needed for the two algorithms, depending on the false alarm rate.

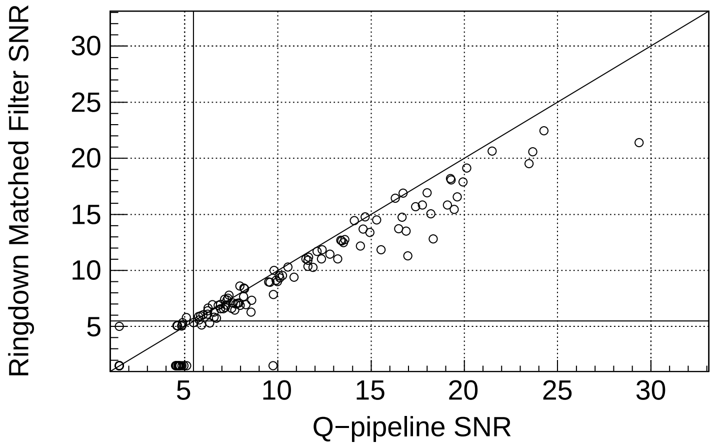

Figure 3. SNR detected by matched filtering to ring-down templates as a function of SNR detected by Q-pipeline for found injections.

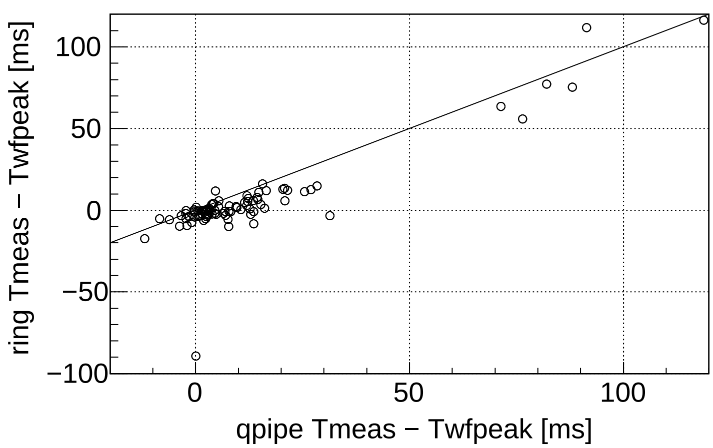

Figure 4. Timing accuracy of detected injection by ring-down search versus Q-pipeline.

3.2. Parameter Estimation

The Q-pipeline identifies a central time for the detected event, corresponding to the peak time for the sine-Gaussian waveform with largest SNR, while the ring-down matched filtering algorithm reports as event time the beginning of the ring-down template with best match to the data. Figure 4 shows the deviation of these two time measurements from the peak time of the injected waveform. The two algorithms are in agreement, with a single outlier, visible in the plot. This event corresponds to a weak injection, close to threshold; in this case, the ring-down code triggered on a startup transient of the signal, 90 ms before the merger.

The Q-pipeline algorithm returns a frequency corresponding to the central frequency of the most significant tile in the time-frequency domain. This frequency,

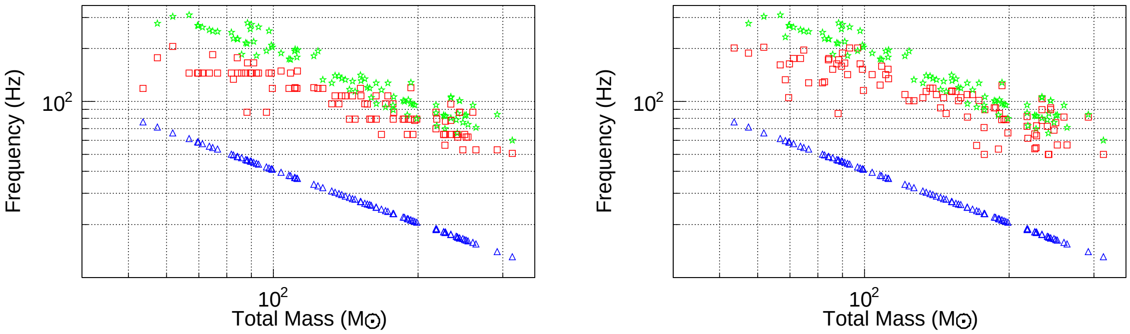

Figure 5. Frequency as a function of mass. Red squares are the frequency returned by Q-pipeline (left) and lalapps_ring (right); In both figures, blue triangles are f_{ISCO}; green stars are f_{ring}.

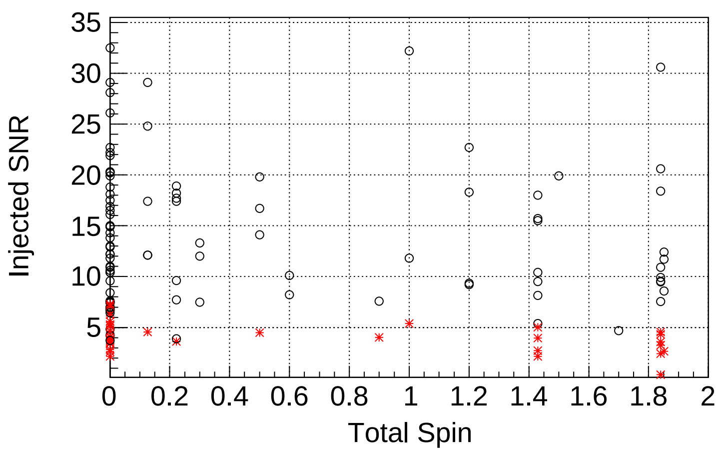

Figure 6. Missed (red stars) and found (black circles) injections for Q-pipeline versus modulus of the total spin a measured in dimension-less spin unit $a = \frac{c}{G}\left(\frac{|\vec{S}_1|}{m_1^2} + \frac{|\vec{S}_2|}{m_2^2}\right)$, being $\vec{S}_i$ the individual spin vectors.

as well as the ring-down frequency from the matched filtering search, are plotted in Figure 5, along with f_{ISCO} and f_{ring}, calculated from the injected parameters according to Equation 1, for comparison. Note that for both algorithms the recovered frequency tends to be from the portion of the coalescence waveform in the most sensitive region of the detector (50-200Hz): the inspiral (in blue) for lower masses, and the ring-down (green) for higher masses. This can be well explained as ISCO and ring-down frequencies are inversely proportional to the total mass of the binary system so, as injection masses increase and frequencies decrease, the portion of the signal falling into the best sensitivity region of the detectors move from the inspiral to the ring-down part of the signal, the largest frequency for any given pair of masses and spins. For the parameters tested in this study, both algorithms detect signals between f_{ISCO} and f_{ring}.

Finally in Figure 6 we show the SNR of missed and found injections for Q-pipeline

as a function of the sum of the spin of the constituents the binary system, each spin being measured in units of individual mass squared: this plot shows no obvious dependence of the detectability on the spin of the black holes.

4. Conclusions

In the context of the Numerical INJection Analysis (NINJA) project, the Q-pipeline burst search algorithm successfully analyzed numerical relativity BBH coalescence waveforms for a variety of masses, spins and eccentricities in simulated colored Gaussian noise. The Q-pipeline single interferometer performance is comparable to matched filtering to ring-down templates, and yields similar arrival time and frequency, and a slightly better SNR. In particular, depending on the total mass of the BBH system, both algorithms trigger between light-ring and ring-down over the broad parameter space covered by NINJA. We emphasize this is a qualitative statement: the statistics of the NINJA data set is too small for a quantitative, systematic comparison. Moreover the absence of the non-Gaussian noise transients typical of real detectors does not allow a realistic estimation of the false alarm rate and threshold settings. Systematic studies will be subjects of future NINJA projects.

5. Acknowledgments

The authors thank the NINJA collaboration for sharing waveforms and simulated data and for useful discussion in the definition of the problems and interpretation of results. This work was supported by grant NSF PHY-0653550 and by the Istituto Nazionale di Fisica Nucleare (INFN).
This paper was assigned number LIGO Document Control Center number P0900068.

References

[1] Aylott B *et al.*, "Testing gravitational-wave searches with numerical relativity waveforms: Results from the first Numerical INJection Analysis (NINJA) project", arXiv:0901.4399 [gr-qc]

[2] Cadonati L *et al.* 2009 *Class. Quantum Grav.* **26** 114008

[3] Hannam M 2009 *Class. Quantum Grav.* **26** 114001

[4] Abbott B *et al.* (LIGO Scientific) 2007 (*Preprint* `0711.3041`)

[5] Smith J, for the LIGO Scientific Collaboration 2009 *Class. Quantum Grav.* **26** 114013

[6] Acernese F *et al.* 2006 *Class. Quantum Grav.* **23** S635–S642

[7] Bruegmann B *et al.* 2008 *Phys. Rev. D* **77** 024027 (*Preprint* `gr-qc/0610128`)

[8] Husa S, Gonzalez J A, Hannam M, Bruegmann B and Sperhake U 2008 *Class. Quant. Grav.* **25** 105006 (*Preprint* `0706.0740`)

[9] Alcubierre M *et al.* 2000 *Phys. Rev. D* **62** 044034 (*Preprint* `gr-qc/0003071`)

[10] Alcubierre M *et al.* 2003 *Phys. Rev. D* **67** 084023 (*Preprint* `gr-qc/0206072`)

[11] Koppitz M *et al.* 2007 *Phys. Rev. Lett.* **99** 041102 (*Preprint* `gr-qc/0701163`)

[12] Pollney D *et al.* 2007 *Phys. Rev. D* **76** 124002 (*Preprint* `0707.2559`)

[13] Imbiriba B, Baker J, Choi D I, Centrella J, Fiske D R, Brown J D, van Meter J R and Olson K 2004 (*Preprint* `gr-qc/0403048`)

[14] van Meter J R, Baker J G, Koppitz M and Choi D I 2006 *Phys. Rev. D* **73** 124011 (*Preprint* `gr-qc/0605030`)

[15] Zlochower Y, Baker J G, Campanelli M and Lousto C O 2005 *Phys. Rev. D* **72** 024021 (*Preprint* `gr-qc/0505055`)

[16] Campanelli M, Lousto C O, Marronetti P and Zlochower Y 2006 *Phys. Rev. Lett.* **96** 111101 (*Preprint* `gr-qc/0511048`)

[17] Sperhake U 2007 *Phys. Rev. D* **76** 104015 (*Preprint* `gr-qc/0606079`)

[18] Hinder I, Vaishnav B, Herrmann F, Shoemaker D and Laguna P 2008 *Phys. Rev. D* **77** 081502 (*Preprint* `0710.5167`)

[19] Pretorius F 2005 *Class. Quant. Grav.* **22** 425–452 (*Preprint* `gr-qc/0407110`)

[20] Pretorius F 2005 *Phys. Rev. Lett.* **95** 121101 (*Preprint* `gr-qc/0507014`)

[21] Scheel M A *et al.* 2006 *Phys. Rev. D* **74** 104006 (*Preprint* `gr-qc/0607056`)

[22] Etienne Z B, Faber J A, Liu Y T, Shapiro S L and Baumgarte T W 2007 *Phys. Rev. D* **76** 101503 (*Preprint* `0707.2083`)

[23] Hannam M, Husa S, Sperhake U, Bruegmann B and Gonzalez J A 2008 *Phys. Rev. D* **77** 044020 (*Preprint* `0706.1305`)

[24] Hannam M, Husa S, Bruegmann B and Gopakumar A 2008 *Phys. Rev. D* **78** 104007 (*Preprint* `0712.3787`)

[25] Tichy W and Marronetti P 2008 *Phys. Rev. D* **78** 081501 (*Preprint* `0807.2985`)

[26] Rezzolla L *et al.* 2008 *Astrpphys.* **J679** 1422–1426 (*Preprint* `0708.3999`)

[27] Vaishnav B, Hinder I, Herrmann F and Shoemaker D 2007 *Phys. Rev. D* **76** 084020 (*Preprint* `0705.3829`)

[28] Buonanno A, Cook G B and Pretorius F 2007 *Phys. Rev. D* **75** 124018 (*Preprint* `gr-qc/0610122`)

[29] Pretorius F and Khurana D 2007 *Class. Quant. Grav.* **24** S83–S108 (*Preprint* `gr-qc/0702084`)

[30] Boyle M *et al.* 2007 *Phys. Rev. D* **76** 124038 (*Preprint* `0710.0158`)

[31] Scheel M A *et al.* 2008 (*Preprint* `0810.1767`)

[32] Santamaria L, Krishnan B and Whelan J 2009 *Class. Quantum Grav.* **26** 114010

[33] Farr B, Fairhurst S and Sathyaprakash B S 2009 *Class. Quantum Grav.* **26** 114009

[34] Stroeer A and Camp J 2009 *Class. Quantum Grav.* **26** 114012

[35] Aylott B, Veitch J and Vecchio A 2009 *Class. Quantum Grav.* **26** 114011

[36] Raymond V *et al* 2009 *Class. Quantum Grav.* **26** 114007

[37] Chatterji S, "The search for gravitational-wave bursts in data from the second LIGO science run", Ph.D. Thesis, MIT Dept. of Physics, 2005

[38] Chatterji S, Blackburn L, Martin G, Katsavounidis E, “Multiresolution techniques for the detection of gravitational-wave bursts”, Class. Quantum Grav. 21 (2004) S1809 (proceedings of the 8th Gravitational Wave Data Analysis Workshop), [arXiv:gr-qc/0412119]

[39] https://geco.phys.columbia.edu/omega

[40] https://www.lsc-group.phys.uwm.edu/daswg/projects/lal.html

[41] Creighton J D E, “Search techniques for gravitational waves from black-hole ringdowns”, 1999 Phys. Rev. D 60 022001

[42] Abbott B P for the LSC, “Search for gravitational-wave bursts in the first year of the fifth LIGO science run” arXiv:0905.0020

[43] Goggin L M, “A search for gravitational waves from perturbed black hole ringdowns in LIGO data”, Ph.D. Thesis, California Institute of Technology, 2008

[44] Abbott B P for the LSC, “Search for gravitational wave ringdowns from perturbed black holes in LIGO S4 data”, arXiv:0905.1654 [gr-qc]

[45] Kidder L E, Will C M, Wiseman A G, “Spin effects in the inspiral of coalescing compact binaries”, Phys Rev D 47 4183 (1993) [arXiv:gr-qc/9211925]

[46] Echeverria F, “Gravitational-wave measurements of the mass and angular momentum of a black hole”, 1989 Phys. Rev. D 40 3194

[47] Goggin L for the LSC, “Search for black hole ringdown signals in LIGO S4 data”, 2006 Class. Quantum Grav. 23 S709-S713

[48] Leaver E W, “Spectral decomposition of the perturbation response of the Schwarzschild geometry”, 1986 Proc. R. Soc. A 402 285

[49] Rezzolla L et al, “On the final spin from the coalescence of two black holes”, gr-qc 0712.3541; Rezzolla L et al, “The final spin from the coalescence of aligned-spin black-hole binaries”, Phys.Rev.D78:044002,2008, arXiv:0710.3345 [gr-qc]

[50] Buonanno A *et al.* 2007 *Phys. Rev. D* **76** 104049 (*Preprint* `0706.3732`)